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TEST OF A NEW MODEL OF FRACTURED ROCK

Final Technical Report

J.B. Walsh and W.F. Brace

30 May 1982

U.S. Army Research Office
Contract Number: DAAG29-79-C-0032

Massachusetts Institute of Technology
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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this program was to study theoretically and experimentally how fluid permeability and electrical resistivity are related to porosity. Also, we proposed to study how these properties change with fluid pressure and confining pressure for the purpose of establishing a law of effective stress for these processes.

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SUMMARY OF TECHNICAL ACCOMPLISHMENTS

Most of the research carried out under this contract involved various studies of rock properties using a new model for fractured rock. We studied primarily permeability and electrical resistivity, although we were led into some related topics during the course of the investigation. The results and accomplishments made possible by the financial support provided by this contract can be divided into four main categories, as follows:

(1) Theoretical studies of resistivity and permeability

We developed expressions showing how permeability and resistivity should vary with confining pressure. These results were published (see [1] under Publications) and presented at two conferences (see [3] and [4]). Briefly, we analyzed a model in which fractures, either large fractures such as joints or small microcracks, are considered to be rough surfaces in contact. Increasing external pressure decreases permeability and resistivity because compression of asperities decreases aperture and increasing the contact area increases the path length. The expression for permeability was compared with data taken from the literature, and good agreement was found. We now have an expression which can be used to predict how permeability will change with pressure which depends only on certain statistical properties of the fracture topography.

Previous experimental studies suggested that permeability k for crystalline rock should be linearly related to resistivity ρ on a log-log plot, i.e., $k = \rho^n$, where experimental values of n varied from 3/2 to 3. We analyzed this problem using a model developed by Wyllie and Spangler in which flow passages were considered to be tubes. We found that the three theoretical analyses of this model contained subtle errors. A correct analysis of this model gives $n = 1$, contrary to experiment. We used our expressions for ρ and k and concluded that n could have values between 1 and 3, although we could not choose a specific value. These results have been presented orally (see [2] and [3]) but have not yet been published.

(2) Effective stress

During the course of the analyses described above, we also analyzed the permeability and resistivity of crystalline rock in experiments where both fluid pressure p_f and confining pressure p_c were varied. We developed an expression for 'effective pressure' p_e in transport processes given by $p_e = p_c - ap_f$, where a can have a value between 0.4 and 1, depending on the topoqraphy of the fracture surfaces. Our expression was found to be reasonably effective in correlating permeability data for the few experiments published in the literature.

The values of a for two experiments described in the literature on a sandstone were found to be greater than unity, apparently due to the day phase which was present. We recently extended our analysis to rocks containing clay. We see qualitative agreement with the observations, but we have not attempted any quantitative verification because of the limited data available. We learned recently of an Austrian scientist who some years ago committed suicide in a fit of depression after losing an argument about effective stress. We don't want to find ourselves in that position.

(3) Experimental studies of permeability and resistivity

Our recent effort has been devoted to measuring the permeability of synthetic rock samples, where porosity and pore shape could be carefully controlled. These experiments allowed us to separate the effects of pore size and tortuosity. (This work is reported in publication [8]). We are now improving the temperature control so that measurements can be made on rocks having even lower porosity than those already tested.

Early in the program, we measured permeability and resistivity for several rock types using a new apparatus design which allowed us to measure both ρ and k on the same sample under the same conditions. With previous equipment, the sample had to be returned to room pressure after permeability had been measured, and then repressurized for the resistivity measurements. This procedure introduced uncertainty because of the different stress history prior to the two measurements and because of possible variation in the test conditions. The experimental portion of the program was set back, first by the loss of the graduate student who was making the measurements, and later by the reduced amount of time that Brace could devote to the laboratory work when he became Department Chairman. The data have proved to be very useful for comparison with previous measurements on the same rock in our laboratory and with measurements from other laboratories. We have not published these results yet because we don't feel that the study is complete.

(4) Miscellaneous studies

Although we generally followed the mainstream during the course of the investigation, we did make several forays up promising tributaries. These analyses are complete but the results have not been published.

(a) Mercury porosimetry. One of the few ways of estimating pore size for rocks is by measuring the amount of mercury forced into samples at various pressures. We analyzed the technique, and developed expressions for correction factors which must be applied to the data and proposed a potentially superior way of making the measurements.

(b) Shear stiffness of joints. Previous analysis considered only the stiffness of joints under stresses acting normal to the joint surface. We developed the corresponding expression when the joint is loaded by small shear stresses, as during the passage of seismic shear wave.

(c) We have developed an expression showing how the flux of a solute diffusing through a fracture is changed when stress is applied normal to the fracture surface. The model and the technique used in the analysis are the same used in the studies of permeability and resistivity described above.

(d) We analyzed the change in porosity which would accompany the failure of asperities, using several models from the friction literature. An internal report describing these results has been prepared, but we have not carried the study further because of the lack of appropriate observations in laboratory experiments.

(e) In connection with our theoretical and experimental studies of permeability, we have been collecting and analyzing *in situ* measurements from drill holes and from certain large-scale phenomena such as reservoir-induced earthquakes. During the present contract period we have updated an earlier review, and written a short paper summarizing new measurements made in crystalline rocks and basalt (see publication 7).

PUBLICATIONS AND TECHNICAL REPORTS

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ADVANCED DEGREES AWARDED

T.-F. Wong, Ph.D., 1981